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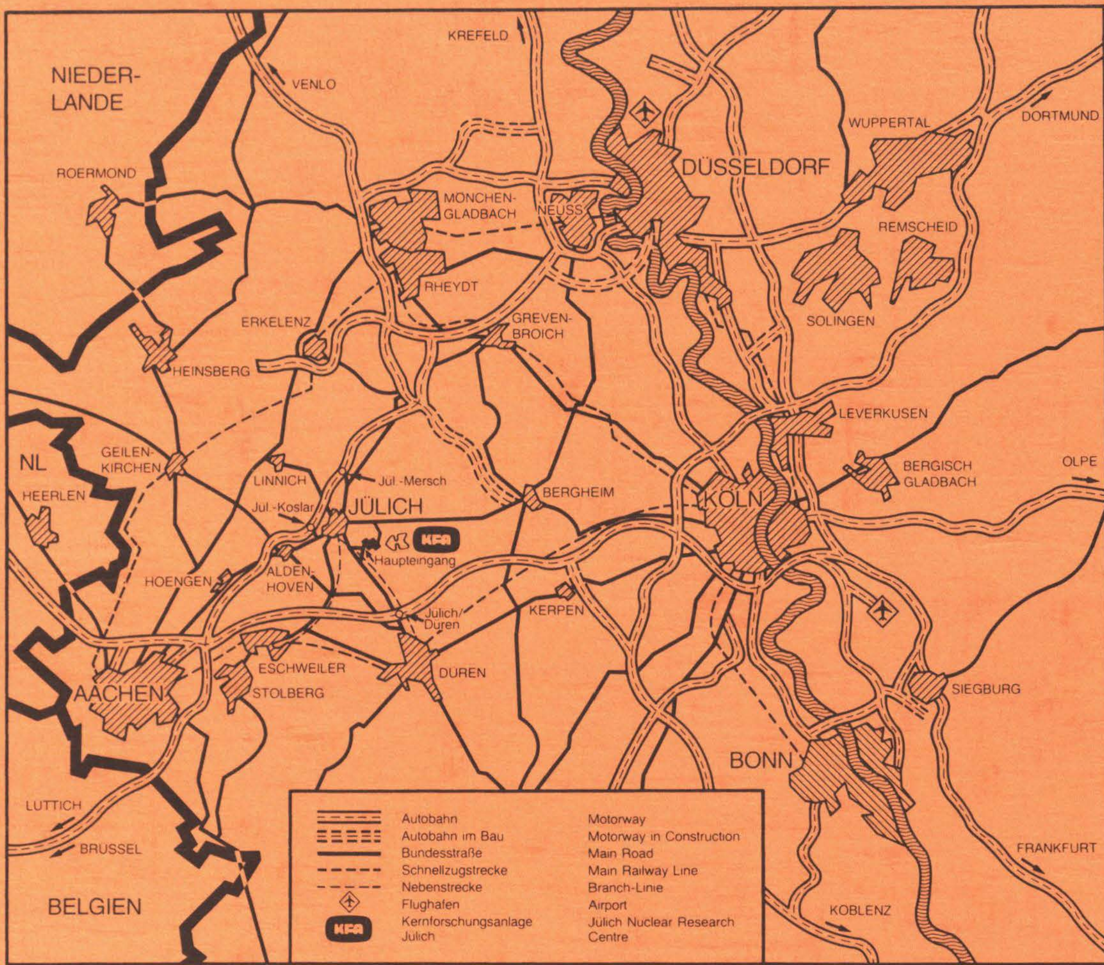

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Statistical Trend Analysis of Dam Failures Since 1850

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February 1984

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ABSTRACT

Evaluating the safety of large dams by means of an average value of failures taken over a long time-span of dam history leads to inadequate results, since it eliminates most of the declining trend. It appears that an analysis that evaluates the trend as such is required to obtain a proper assessment of the safety performance as a basis for failure prognosis and thereby for decision making on investments.

Trends appear in dependencies on three different variables: year of failure, year of construction,and age. Two different methods are presented to analyze these trends: one method for the trend analysis of the failure occurrence in time for a dam population, and a second method for the combined analysis of trends in the construction year and age dependencies. The first method is applied to large dams in the U.S.A. and in Western Europe built after 1850, combined as well as for individual dam types, whereas the second method is only applied to U.S. embankment dams because of its more extensive data requirements.

I. INTRODUCTION

The economic importance of dams for water, food and energy supply led to the construction of a large number of dams, especially in the recent fifty years. The "World Register of Dams" (Ref. 1) lists in 1973 over 13,000 large dams, characterized essentially by their height being larger than 15 m. As larger dams are impressive constructions, failures or ruptures of large dams are spectacular and widely recognized accidents, sometimes with disastrous consequences. The increased interest of the public in safety and risk requires an adequate description of the safety performance of dams, especially large dams.

Dam safety is sometimes quantified in terms of an overall historical average of about 1 % chance of a dam to rupture, leading to a total loss. Such a characterization is inadequate as it disregards the technical progress that led to an impressive improvement of dam safety. This becomes evident in a number of detailed analyses that aim at a description of this technical progress, e.g. Schnitter, 1967 (Ref. 2) and 1976 (Ref. 3), Rissler, 1981 (Ref. 4), Serafim, 1981 (Ref. 5), Vogel, 1982 (Ref. 6) and Blind, 1982 (Ref. 7). Typical quantification concepts employed were "failures per dam-year," the "fraction" or "percentage of dams failed," and the age dependency of failure occurrences.

A general problem of these statistical analyses is that terminal ruptures of dams are "rare events". This is even more so when the entire dam population is subdivided in smaller categories, be it by distinguishing dam types (such as concrete or embankment dams), or by introducing differentiated height limitations (e.g. larger than 15 meters, or larger than 40 meters), by grouping dams by geographical location (e.g. U.S.A. vs Western Europe) or by distinguishing causes of failures. But problems of analysing a sparse statistical data base are not limited to dam failures.

Recently, improved statistical techniques have been developed addressing the three quantification concepts mentioned above. In Refs. 8 through 10 a method for trend analysis of "failure rates per operation-year" in a population of technical systems is developed. Reference 11 is concerned with a refined evaluation of the fraction of units failed, as a function of the construction year, that appears to be a suitable concept for the demonstration of the technical progress. In addition, the age distribution of failure occurrences is investigated in Ref. 11. In this paper the methods developed in Refs. 8 through 11 are proposed for the investigation of dam safety.

In Sect. II the approach of Refs. 8 to 10 is briefly reviewed; it is subsequently applied to the trend analysis of failure rates per operation year of dams in the U.S.A. and Western Europe, including separate analyses of embankment and concrete dams as well as a differentiation with respect to causes of failures. Section III then addresses the failure ratio, the age distribution of failures, and the "failure potential" that may still be contained in a given population, or its "marginal" value that is added in a certain construction period.

The results of these statistical analyses can and should be related to the historical development of the technology of dam design and construction. As the authors of this paper have no expertise in this area no attempt is made here to specifically relate the various identified trends to particular technological developments.

II. FAILURE RATE TRENDS FOR POPULATIONS OF LARGE DAMS

II.1 Trend Analysis of Rare Events in Terms of Failure Rates

Major failures of large technical systems such as large dams are comparatively "rare" events. "Rare" in this context means that the average time-span between two or a very few failure events is so large that the technical progress during this time is not insignificant. In these cases then a sparse data base is being assembled while the technology is changing underneath. In such a situation, average values of failure rates formed over longer periods of time are not the best characterization.

Dividing the number of failures during the entire operation of a technology prior to time t by the total number of operation years yields a "historical average failure rate" per operation year, say $\bar{L}^H(t)$. If this "running" historical average value were — aside from statistical fluctuations — independent of t, the characterization of the entire operation history by a simple average value would be justified. However, if newer units are safer as it is the case for large dams and most other technologies, $\bar{L}^H(t)$ tends to decrease. This indicates a learning effect or technical progress. If $\bar{L}^H(t)$ decreases in a statistically significant way, it does not properly reflect the failure rate of existing populations of technical units, since it combines failures in old and new technologies without explicit allowance for safety improvements. It may contain failure modes that are no longer possible or are by now much less likely than in the past. A more sophisticated analysis is then called for.

Knowledge of the technical progress in dam building, supported by a statistically significant decrease in $\bar{L}^H(t)$, as shown below, provides "prior information" that can be exploited in the statistical analysis. Instead of lumping the information in average values, one tries to extract a "trend" from the stochastically varying data. Regression procedures for this purpose often employ an analytical function with free parameters (e.g. linear, parabolic or exponential functions) that are determined by a least square procedure. The "isotonic regression" proposed here for the analysis of trends in dam failure rates does not employ continuous functions; it requires the estimates to be monotonous, reflecting the notion of a monotonous technical progress. If the actuarial data should not be consistent with the trend assumption, the procedure would yield a constant rate estimate, actually the same value as $\bar{L}^H$ for the particular time. The trend analysis procedure using isotonic regression is presented in Refs. 8 through 10. Here only the main concepts are reviewed as a basis for the subsequent application.

The procedure is based on the operation-time differences, ΔT_k, between successive failure events, numbered k-1 and k. It yields as isotonic estimates the set of values, $\Delta\hat{T}_k$, with

$$\Delta\hat{T}_k \geq \Delta\hat{T}_{k-1}$$

for all k (if prior information suggested an improvement of the safety performance). The stochastic variations that normally perturb the monotony of the ΔT_k have been eliminated in the evaluation of the $\Delta\hat{T}_k$.

The inverse values of these $\Delta\hat{T}_k$ yield the desired failure rate estimates:

$$\hat{L}_k = 1/\Delta\hat{T}_k.$$

The $\hat{L}_k$ represent then a declining failure rate for the investigated dam population, that allows learning and technical progress to manifest itself in terms of a generally decreasing sequence of $\hat{L}_k$:

$$\hat{L}_1 \geq \dots \geq \hat{L}_{k-1} \geq \hat{L}_k.$$

If over some periods of time statistical fluctuations overshadow an underlying technical progress, the $\hat{L}_k$ in this period will appear to be the same (see the numerical results and the corresponding discussion in II.2.).

A tentatively identified trend needs to be evaluated for its statistical significance. Methods to evaluate the trend significance are indicated in Ref. 10.

The application of this trend analysis procedure to failures of large dams is presented in Sec. II.2.

II.2 Trend Analysis of Dam Failure Rates in USA and Western Europe

The data of dam failures used in this analysis are presented in Tables 1 through 4, with dam ruptures listed in chronological order, beginning 1850. In addition to the name of the dam, its construction year, the tables contain the dam type and height, and the cause of the failure given as overtopping, seepage, foundation failure, and others. Tables 1 and 2 list embankment dam failures and Tables 3 and 4 concrete dam failures, in both cases for USA and Western Europe (W.E.) respectively.

Based on the failure dates and detailed information on construction dates for all large dams, the number of operation years, the ΔT_k, between successive failures were evaluated. The ΔT_k were then subjected to isotonic regression, yielding the monotonously stretched sequence of $\Delta\hat{T}_k$-values. Both, the ΔT_k and the $\Delta\hat{T}_k$ are listed in Table 5 for embankment dams in USA and for concrete dams in USA and W.E. respectively. The large number of embankment dam failures in USA allowed a differentiation with respect to failure causes. The corresponding ΔT_k and $\Delta\hat{T}_k$ values are listed in Table 6.

Figure 1 represents $\hat{L}_k$, the inverse sequence of the $\Delta\hat{T}_k$, i.e. the failure rates per operation year for embankment and concrete dams in USA and W.E., plotted over a linear time axis of the failure years. In all three diagrams the failure rates show a strongly declining trend, by about a factor of 40 for US embankment dams. Concrete dams show an even stronger decrease. The overall failure frequency of dams in Western Europe, especially before 1930, appears to be considerably lower than that of US dams. All failure rate diagrams indicate a remarkable improvement of the level of safety in these dam populations.

The overall declining trend of failure rates presented in Fig. 1 (and below in Fig. 2) is interrupted by periods of "constant" rate estimates. Over these periods, statistical fluctuations appeared in a form of particularly small time intervals, ΔT_k, that obscure and overshadow the underlying trend of increasing ΔT_k and thus decreasing failure rates L_k. It should be noted that a sequence of constant $\Delta\hat{T}_k$ values does not suggest an actual constant failure rate; it merely means that the estimation procedure cannot discern a declining rate. Mostly, such periods of constant rate estimates are followed by periods of above average decline estimates, where the statistical fluctuations of the intervals ΔT_k appear in the opposite direction.

In addition to the total frequency of US embankment dam failures shown in Fig. 1, individual causes are considered in Fig. 2. (It should be noted, however, that there is no rigorous additivity within this group of $\hat{L}_k$-histograms, because the isotonic regression is independently applied to each set of data.)

III. FAILURE RATIO, FAILURE AGE DISTRIBUTION, FAILURE POTENTIAL

III.1 Evaluation of the Actuarial Information, the Failure Ratio and the Age Distributions

The failure trend analysis presented in Sec. II.1 evaluates the safety behavior of an existing population comprised of units of different vintage. The results of this trend analysis show a considerable decline of the failure rate per operation year as a function of time that exhibits an "average" learning process for this varying aggregate of large dams. For an investigation of the relation of the corresponding technical progress with a failure rate trend it is however more important to analyze the specific trend of dams as a function of the construction year (t^c). In addition, there is the age distribution of failure events, that — in proper combination with the construction year dependency — make up the failure trend of the dam aggregate. A procedure for the evaluation of these concepts is presented in Ref. 11. Here only the main concepts are outlined as a basis for the subsequent application.

The actuarial data on failure events as a function of the two variables, construction year t^c and age τ, can be represented as dots in a t^c-τ diagram, that may be called the failure date matrix. Figure 3 shows as an example the failure date matrix for large U.S. embankment dams with failures between 1850 and 1975, i.e. for a period of 125 years. The specific rupture events depicted in Fig. 3 are listed in Tab. 1.

The "failure ratio" $S(t^c, \tau_s)$ measures the chance for a failure as a function of the construction year; more precisely, it is the fraction of the $b(t^c)$ dams, constructed in the "year" t^c (or construction period t^c), that has a (major) failure during a designated operation period τ_s after construction. Since major failures are unlikely events, the chance for a second failure is remote; it is therefore disregarded in the following analysis.

Since failures do not occur evenly distributed as a function of their age τ, one introduces a function $K(t^c,\tau)$ that describes the distribution of the $b(t^c)$ $S(t^c,\tau_s)$ failures within the considered age interval $0 \leq \tau \leq \tau_s$.

First approximations for the quantities S and K can be obtained from the presentation of the actuarial data in Fig. 3. The procedure developed in Ref. 11 is a refined evaluation of $S(t^c,\tau_s)$ and $K(t^c,\tau)$.

The first approximations S and K, denoted by $S_1(t^c)$ and $K_1(\tau)$ respectively, can be obtained from Fig. 3 by summing up failure events along respective directions, keeping the other variable constant: Horizontal summation yields $b(t^c)$ $S_1(t^c)$; the vertical summation yields at first the number of failures at age τ, i.e. $M(\tau)$. It can be readily converted in a normalized age distribution, $K_1(\tau)$, by dividing by its integral.

Since dam failures are rare events, it is necessary for these summations to choose larger than annual intervals. The size of the intervals depends on the actuarial data as such; one always has to make a compromise between trend identification and statistical error. The set of intervals for t^c and τ shown in Fig. 3 results from trying to have the relative statistical errors comparable to the change of the respective continuous approximations through each interval. In some cases, this may even suggest to have only one event in an interval. The chosen τ-intervals vary greatly with age. The first four τ intervals are only 1, 1, 2 and 6 years. The next four intervals are just one decade each, followed by a 70 year interval with a single failure. It appeared meaningful for trend identification to allow a larger statistical error in this interval.

The first column in fig. 3 gives the number of units built in each t^c interval, denoted by b_Δ. The next column lists the number of the corresponding ruptures which equals b_Δ times the average failure fraction $\bar{S}_1$. The row at the bottom of Fig. 3 notes the number of failures in the chosen age-intervals, i.e. $M_\Delta(\bar{\tau})$.

Statistical errors around the interval-values listed in Fig. 3, regarded as best estimates, are obtained in terms of 68 % confidence intervals by standard formulas. Figure 4 shows the interval values with the respective confidence intervals for $S_1(t^c)$ and $M(\tau)$. These values suggest the presence of significant trends in $S_1(t^c)$ as well as $M(\tau)$, since early and later values are separated by several 68 % confidence intervals. Only if these intervals would overlap the assumption of a constant failure rate would have some justification, and with it the formation of a historical average value. This is obviously not the case.

The interval-values, $S_1(\bar{t}^c)$ and $K_1(\bar{\tau})$, provide statistically fluctuating information on the respective underlying variations, $S_1(t^c)$ and $K_1(\tau)$, that should be fairly continuous. Therefore, continuous estimations are derived from the interval values. For details of these continuous approximations, see Ref. 11, where dam safety has been used as an example for the illustration of the methodology.

The age dependency $M(\tau)$ is approximated by a sum of two expontential functions*:

$$M(\tau) = a_1 e^{-b_1\tau} + a_2 e^{-b_2\tau} .$$

* a_1 = 8/yr; a_2 = 1/yr; b_1 = 0.5/yr; b_2 = 0.05/yr

A large value for b_1 accounts for rapid decrease of dam failures during the first few years of operation, that to a large extent should result from a decrease in the chance for foundation failures (see Fig. 4).

The continuous approximation for the actuarial failure ratio in Fig. 4 is represented by a modified Gaussian*:

$$S_1(t^c) = c_1 \exp\left[-\left(\frac{t^c - t_0^c}{c_2}\right)^{c_3}\right] \quad .$$

An approximation like this might suggest a slow technical progress in the last century, but an increasingly rapid improvement of dam safety throughout this century.

III.2 Completion of the Failure Information

The quantities $S_1(t^c)$ and $K_1(\tau)$ are based on the summations over the actuarial information, i.e. over the left lower triangle in Fig. 3. They are approximations for the underlying idealized functions $S(t^c,\tau_s)$ and $K(\tau,t^c)$ that pertain to the same operating period τ_s for all t^c. The diagonal in Fig. 3 corresponds to the end of the observation period for each t^c, whereas the "completed" quantities S and K are defined in the rectangle that is indicated in Fig. 3 by a dotted line. Thus, future failure events have to be projected into the upper triangle. This is feasible for dam failures if the age dependency $K(\tau,t^c)$ is assumed to be independent of t^c, i.e. $K(\tau,t^c) \simeq K(\tau)$. The function of $K(\tau)$ is then to be derived from the actuarial data as proper average value. (For technologies with a rich failure data statistics it may be possible to infer $K(\tau,t^c)$

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* $c_1 = 0.15$; $c_2 = 3.3 \cdot 10^4$ yr; $c_3 = 2.5$

as basis for an improved projection procedure.).

The average $K(\tau)$ cannot be found independently of $S(t^c,\tau_s)$. It is shown in Ref. 11 that $K(\tau)$ and $S(t^c,\tau_s)$ are related to each other by a coupled system of two integral equations, that contain the actuarial information in terms of $S_1(t^c)$ and $M(\tau)$. The (iterative) solution of this equation yields simultaneously S and K.

The completion of S_1 and K_1 by the evaluated functions $S(t^c,\tau_s)$ and $K(\tau)$ is shown in Figs. 5 and 6. The difference between S_1 and S as well as between K_1 and $K(\tau)$ is not very large over most of the observation period. The reason is that $K(\tau)$ decreases very strongly. Therefore, during the first few decades, depicted in Fig. 5, $S(t^c)$ is quite close to $S_1(t^c)$, since nearly all failures that can be expected in the present dam population have already occurred. However, toward the end of the observation period, $S(t^c)$ is about 70 % larger than $S_1(t^c)$, a difference that is not unimportant in view of the large number of existing dams (nearly 4000).

The difference between $S(t^c)$ and $S_1(t^c)$ can also be expressed in terms of additional failures that may have to be expected in the future. The completion procedure applied here yields 6.4 additional failures in the considered embankment dam population of about 4000 large dams in addition to the 40 failures that have occurred in the past.

Figure 6 shows the comparison of $K_1(\tau)$ with $K(\tau)$. Since the total observation period amounts to more than 120 years, the failures during the first 30 years of age are documented by a large part of the existing population. Only for dams of the present population that are or will be older than about 30 years*, the applied completion procedure yields an addition to $K_1(\tau)$ as indicated in Fig. 6. The turn from $K_1(\tau)$ into $K(\tau)$ could be interpreted as an indication of a "bathtub"-type curve leading to an increasing failure probability for large age ($\gtrsim$ 100 years). But the

* but not more than τ_s years

statistical information is not sufficient to draw such a conclusion; there is only a single failure between 50 and 120 years of age in the evaluated dam population.

III.3 The Failure Potential

From $S(t^c)$ and the construction rate $b(t^c)$ one obtains the "marginal failure potential," i.e. the failure potential added in the construction "year" t^c:

$$P(t^c) = S(t^c)\ b(t^c).$$

Apparently, the marginal failure potential, P, is related to the annual failure rate, $\Lambda(t)$, by the convolution integral

$$\Lambda(t) = \int_{t_o}^{t} P(t^c)\ K(t-t^c)\ dt^c;$$

i.e. $\Lambda(t)$ is a composite of earlier additions of potential failures multiplied with the probability that they occur at age $\tau = t-t^c$. Here, t_o is the beginning of the observation period. If $K(\tau)$ is as strongly decreasing as it is the case for large dams (50 % of all failures occur during the first 5 years of operation for the data used here), $\Lambda(t)$ "follows" $P(t^c)$ with a few years delay. This appears to be confirmed by Fig. 7. The strong addition of failure potential between 1900 and 1920 is followed by noticeable increase in the actual annual failure rate, $\Lambda(t)$. Since about 1920 however, the improvement in dam safety has been overcompensating the increasing construction rate.

III.4 Failure Ratios and Age Distributions for Different Causes

The number of dam failures is too small to allow the application of the statistical completion analysis for individual causes. However, a combination of the completed results, $S(t^c)$ and $K(\tau)$, for the entire U.S. embankment dam population with the historically observed fractions of the various causes can provide some first order approximations. The results of this "combination" are depicted in Fig. 8 in the following way:

The information on causes as well as on the magnitude of the failures (distinguishing totally lost from repaired dams) is portrayed as subdomains of squares. The size of the squares is related to the magnitudes of the continuous functions $K(\tau)$ and $S(t^c)$ respectively at the midpoints of the considered τ and t^c intervals. These intervals are chosen such that information on 10 failures is available to break up the squares into subdomains for the various causes. In this way it is possible to recognize improvements in the different cause categories as size reductions in the corresponding areas. It should be noted, however, that indicated trends of individual causes have considerable statistical inaccuracies because of the small number of ruptures.

The upper figure shows that a large fraction of younger dams is reconstructed, but only a small fraction of older dams since they may be close to the end of their economic lifetime. Early in the dam life, especially during the first filling, foundation failure and seepage are known to be the most likely causes of failure, failures that are in a sense built-in by flaws in the design or the construction. Whereas the chance for foundation failures seems to diminish after some period of operation, seepage continues to be a failure cause throughout the dam's life.

In the lower diagram some variations seem to be indicated in the dependence of $S(t^c)$, somewhat higher values for foundation failures around 1905, and for overtopping around 1920. Again, because of the small numbers, statistical fluctuations may overshadow the actual progress in the prevention of various causes of failures.

SUMMARY

For the statistical evaluation of the evolution of the safety performance of large dams, two methods are proposed and applied in this paper. The two methods address different measures of the safety performance. Both methods have been specifically devised for the analysis of "rare" events, where "rare" means that the average time-span between two (or a very few events) is so large that the technical progress during this time is not insignificant. Because of the substantial advance of dam design and construction methods, the characterization of the safety performance by a long-term averaged failure rate is inadequate.

The first method addresses the "failure rate per dam-year" for various populations of large dams ($\geq$ 15 m), embankment and concrete dams in USA and Western Europe, between 1850 and 1975. The regression method applied allows for learning and technical progress to manifest itself in terms of a reduction of the failure rate per dam-year with time. The time intervals for this analysis are not arbitrarily imposed; they are determined by the regression procedure itself, based on the statistics of the actuarial failure-interval data.

Examples of the numerical results obtained indicate a reduction of the failure rate of U.S. embankment dams from 0.8/100 around 1860 to 1.4/10,000 around 1975. For U.S. concrete dams the reduction was even stronger, i.e. from 0.6/100 (late last century) to less than 0.6/10,000 dam years beginning 1935. Similar, but generally somewhat smaller numbers are obtained for Western Europe.

For U.S. embankment dam failures, a differentiation with respect to failure causes is possible. Results for failure rates are presented for the cause categories, overtopping, seepage, foundation failure and "others".

A second class of questions is concerned with the chance of a failure for dams of different vintage (or construction year, t^c). The actuarial information for the time from construction to the end of the observation period gives a first measure, the observed failure ratio, $S_1(t^c)$. By deriving information on the age dependency of failure events $[K(\tau); \tau = \text{age}]$ and extending the failure age distribution into the future, one can find a failure ratio $S(t^c,\tau_s)$ that pertains to the same operation period τ_s for all construction years, t^c.

An evaluation of the failure ratio $S(t^c)$ and the age distribution $K(\tau)$ has been performed for U.S. embankment dams from 1850 through 1975. The extension of $S_1(t^c)$ by considering possible future failures consistent with the previous age distribution $K(\tau)$ indicates that about 6 or 7 dams of the present population of 4000 might fail in the future.

Finally, the failure ratio $S(t^c)$ allows us, through multiplication with the construction rate $b(t^c)$, to define a "marginal failure potential," that is added in the "year" t^c. Because $K(\tau)$ is strongly decreasing with age, a major peak in the addition of failure potential can show up as a similar increase in the annual failure rate in the ensuing years.

TABLE 1

U.S. Embankment Dam Failures 1850 - 1980 (Height ≥ 15 m)*

No.	Name	Year of construction	Year of rupture	Dam Type**	Height [m]	Repair	Reservoir Capacity [$10^6 m^3$]	Cause
1	Cuba Reservoir	1851	1868	earth	16	yes		unknown
2	South Fork (Johnstown)	1852	1889	earth/rock	22	no	19.0	overtopping
3	Walnut Grove	1888	1890	rock	34	no	11.0	overtopping
4	Chamberslake (1st failure)	1885	1891	earth	17	yes	10.0	overtopping
5	Snake Ravine	1898	1898	earth	19	no		seepage
6	Lake Francis	1899	1899	earth	15	yes	0.9	seepage
7	Utica Reservoir	1874	1902	earth	21	no	0.7	other
8	Greenlink (Scottdale)	1901	1904	earth	18	yes	1.0	foudation failure
9	Chamberslake (2nd failure)	1892	1907	earth	17	yes	10.0	unknown
10	Black Rock (Zuni)	1907	1909	earth/rock	21	yes	19.5	foundation failure
11	Julesburg	1905	1910	earth	16	yes	34.7	foundation failure
12	Hebron (1st failure)	1913	1914	earth	17	yes		seepage
13	Hatchtown	1908	1914	earth	18	no	1 .0	seepage
14	Horse Creek	1912	1914	earth	17	yes	20.9	foundation failure
15	Sepulveda Canyon	1914	1914	earth	19	no	0.2	overtopping
16	Lyman	1913	1915	earth	19	yes	49.3	foundation failure
17	Lake Toxaway	1902	1916	earth	18	no	3.7	foundation failure
18	Long Tom	1906	1916	earth	18	yes		seepage

* Sources: Refs. 1, 3 to 7 , and 12 to 28

** earth = earth filled,
earth/rock = earth and rock filled,
rock = rock filled embankment dam

Table 1 continued

No.	Name	Year of construction	Year of rupture	Dam Type	Height [m]	Repair	Reservoir Capacity [$10^6 m^3$]	Cause
19	Lookout Shoals	1915	1916	earth	25	yes	49.0	overtopping
20	Lower Otway	1886	1916	earth/rock	39	no	39.6	overtopping
21	Schaeffer	1911	1921	earth	30	no		overtopping
22	Apishapa	1920	1923	earth	34	no	23.0	seepage
23	Graham Lake	1922	1923	earth	34	no		foundation failure
24	Mc Mahon Gulch	1924	1926	earth	16	yes		overtopping
25	Balsams	1927	1929	earth	18	no		overtopping.
26	Corpus Christi	1930	1930	earth	18	yes	78.9	foundation failure
2.	Wagner	1918	1938	earth	15	no	0.7	overtopping
28	Anaconda	1898	1938	earth	21	no	0.3	seepage
29	Hebron (2nd failure)	1913	1942	earth	17	no		overtopping
30	Sinker Creek	1910	1943	earth	21	no	3.3	seepage
31	Fred Burr	1947	1948	earth	16	yes	0.64	seepage
32	Stockton Creek	1949	1950	earth	29	yes	0.5	seepage
33	Baldwin Hills	1951	1963	earth	80	no	1.0	foundation failure
34	Little Deer Creek	1962	1963	earth	25	no	1.8	seepage
35	Jenning Dam No. 3	1962	1963	earth	21	yes	0.43	foundation failure
36	Swift	1914	1964	earth/rock	57	no	37.0	overtopping
37	Emery	1850	1966	earth	15	no		seepage
38	Sheep Creek	1969	1970	earth	18	yes		seepage
39	Whitewater Brook Upper	1943	1972	earth	18	no	0.5	overtopping
40	Walter Bouldin	1967	1975	earth	50	yes		other
41	Teton	1975	1976	earth	92	no	355.0	seepage

TABLE 2

West European Embankment Dam Failures 1850 - 1980 (Height ≥ 15 m)

No.	Name	Year of construction	Year of rupture	Dam Type	Height [m]	Repair	Reservoir Capacity [$10^6 m^3$]	Cause
1.	Woodhead (U.K.)	1851	1851	earth	26	yes		foundation failure
2.	Dale Dike (U.K.)	1858	1864	earth	29	no	3.1	seepage

Sources: see Table 1

TABLE 3

U.S. Concrete Dam Failures 1850 - 1980 (Height ≥ 15 m)

No.	Name	Year of construction	Year of rupture	Dam Type	Height [m]	Repair	Reservoir Capacity [$10^6 m^3$]	Cause
1	Angels	1895	1895	gravity	16	no		foundation failure
2	Austin Texas	1893	1900	gravity	20	yes	21.0	overtopping
3	Austin (Pa.) (Bayless)	1909	1911	gravity	15	no	0.8	foundation failure
4	Stony River	1913	1914	buttress	15	yes	11.4	foundation failure
5	Owerholser	1920	1923	buttress	16	yes	19.0	overtopping
6	Lake Lanier (Vaugh Creek)	1925	1926	arc	18	no		foundation failure
7	Moyie River	after 1920	1926	arc	16	no		overtopping
8	St. Francis	1926	1928	gravity	56	no	47.0	foundation failure
9	Castelewood	1890	1933	gravity	28	no	4.3	overtopping
10	Lake Barcroft	1913	1972	gravity	21	yes		overtopping

Sources: see Table 1

TABLE 4

West European Concrete Dam Failures 1850 - 1980 (Height ≥ 15 m)

No.	Name	Year of construction	Year of rupture	Dam Type	Height [m]	Repair	Reservoir Capacity [$10^6 m^3$]	Cause
1	Bouzey (France)	1888	1895	gravity	22	no	7.0	other
2	Gleno (Italy)	1923	1923	buttress	49	no	5.4	foundation failure
3	Zerbino (Italy)	1924	1935	gravity	16	no	8.0	overtopping
4	Vega de Tera (Spain)	1956	1959	buttress	34	no	8.0	other
5	Malpasset (France)	1954	1959	arc	66	no	48.0	foundation failure
6	Bacino di Rutte (Italy)	1952	1965	buttress/ arc	15	no	0.31	foundation failure

Sources: see Table 1

TABLE 5: Time Spacings and Their Isotonic Estimate

U.S.A. embankment dams			U.S.A. concrete dams			W.E. concrete dams		
k	ΔT_k	$\Delta\hat{T}_k$	k	ΔT_k	$\Delta\hat{T}_k$	k	ΔT_k	$\Delta\hat{T}_k$
1	130	130	1	201	168	1	684	684
2	504	189	2	134	168	2	3106	3106
3	44	189	3	681	566	3	4082	4082
4	45	189	4	451	566	4	16130	8129
5	385	189	5	2000	932	5	565	8129
6	65	189	6	752	932	6	7692	8129
7	232	189	7	173	932			
8	186	189	8	763	932			
9	341	189	9	2147	2147			
10	283	189	10	25571	16290			
11	168	189	11	7009	16290			
12	663	189						
13	59	189						
14	59	189						
15	60	189						
16	246	189						
17	64	189						
18	64	189						
19	64	189						
20	64	189						
21	1379	673						
22	475	673						
23	165	673						
24	1096	951						
25	1289	951						
26	468	951						
27	4098	1989						
28	320	1989						
29	2786	1989						
30	752	1989						
31	3891	2828						
32	1764	2828						
33	15900	4675						
34	602	4675						
35	602	4675						
36	1938	4675						
37	4329	4675						
38	10300	7260						
39	5750	7260						
40	9620	7260						
41	3370	7260						

k = failure number

ΔT_k = operation-time difference of the population of dams between successive failure events numbered k-1 and k (years)

$\Delta\hat{T}_k$ = isotonic estimate of ΔT_k (years)

TABLE 6: Time Spacings and Their Isotonic Estimate for US Embankment Dams by Causes of Failures

	all causes		overtopping		seepage		foundation failure		others	
k	ΔT_k	$\Delta \hat{T}_k$	ΔT_k	$\Delta \hat{T}_k$	ΔT_k	$\Delta \hat{T}_k$	ΔT_k	$\Delta \hat{T}_k$	ΔT_k	$\Delta \hat{T}_k$
1	130	130	614	234	1075	570	1539	600	130	130
2	504	189	43	234	65	570	599	600	1235	872
3	44	189	44	234	1630	818	159	600	508	872
4	45	189	2174	965	105	818	578	600	66667	66667
5	385	189	595	965	719	818	472	600		
6	65	189	125	965	2000	2000	251	600		
7	232	189	1351	1351	7092	4040	2000	2000		
8	186	189	1695	1473	3484	4040	2778	2778		
9	341	189	1250	1473	3861	4040	29430	15150		
10	283	189	4785	3763	1724	4040	870	15150		
11	168	189	2740	3763	16393	10818				
12	663	189	25000	22500	6061	10818				
13	59	189	20000	22500	10000	10818				
14	59	189			18519	18519				
15	60	189								
16	246	189								
17	64	189								
18	64	189								
19	64	189								
20	64	189								
21	1379	673								
22	475	673								
23	165	673								
24	1096	951								
25	1289	951								
26	468	951								
27	4098	1989								
28	320	1989								
29	2786	1989								
30	752	1989								
31	3891	2828								
32	1764	2828								
33	15900	4675								
34	602	4675								
35	602	4675								
36	1938	4675								
37	4329	4675								
38	10300	7260								
39	5750	7260								
40	9620	7260								
41	3370	7260								

k = failure number

ΔT_k = operation-time difference of the population of dams between successive failure events, numbered k-1 and k

$\Delta \hat{T}_k$ = isotonic estimate of ΔT_k (years)

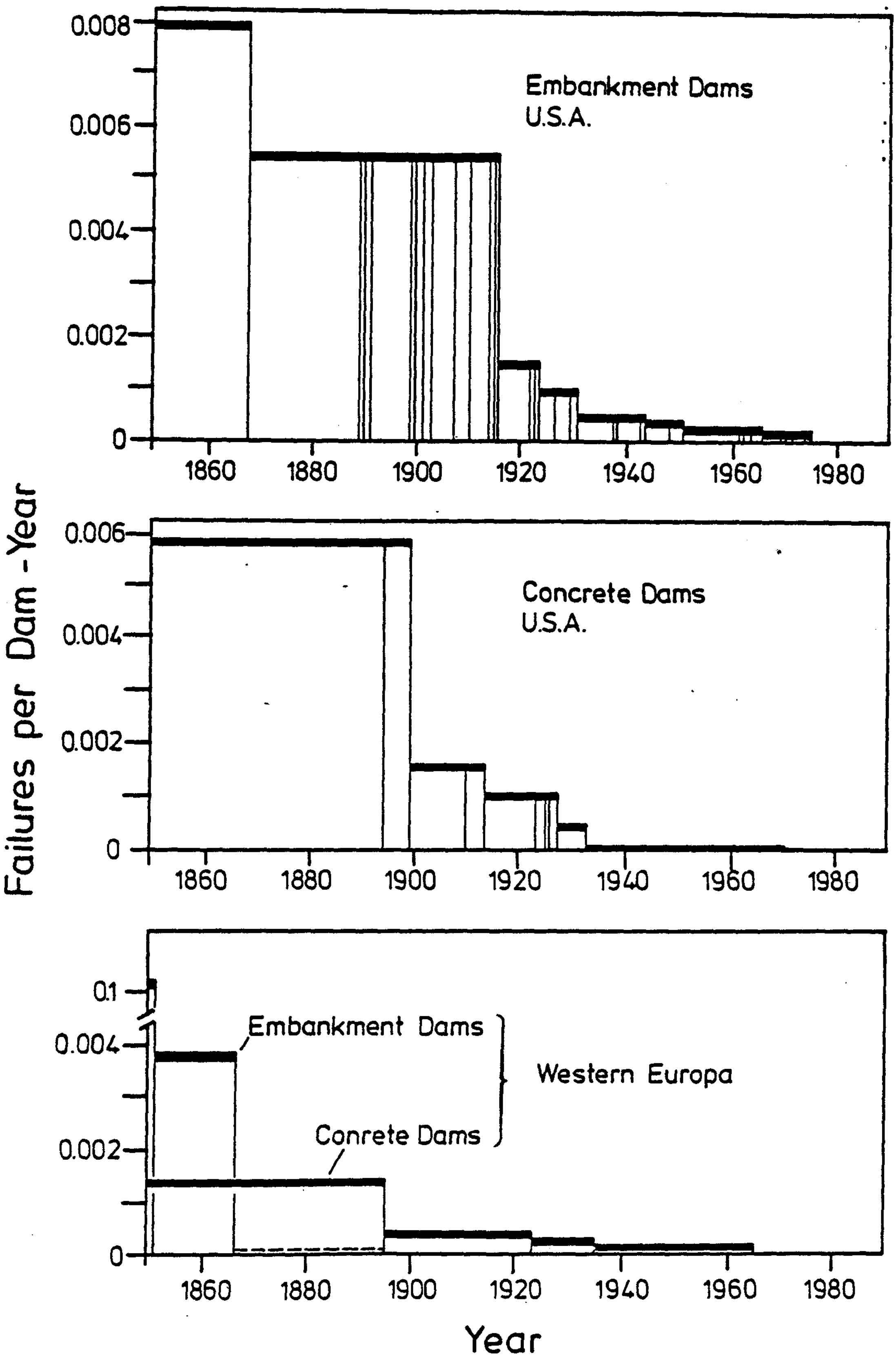

Fig. 1: Isotonic regression estimates for the failure rate per operation year, $\hat{L}$, by dam-types and locations.

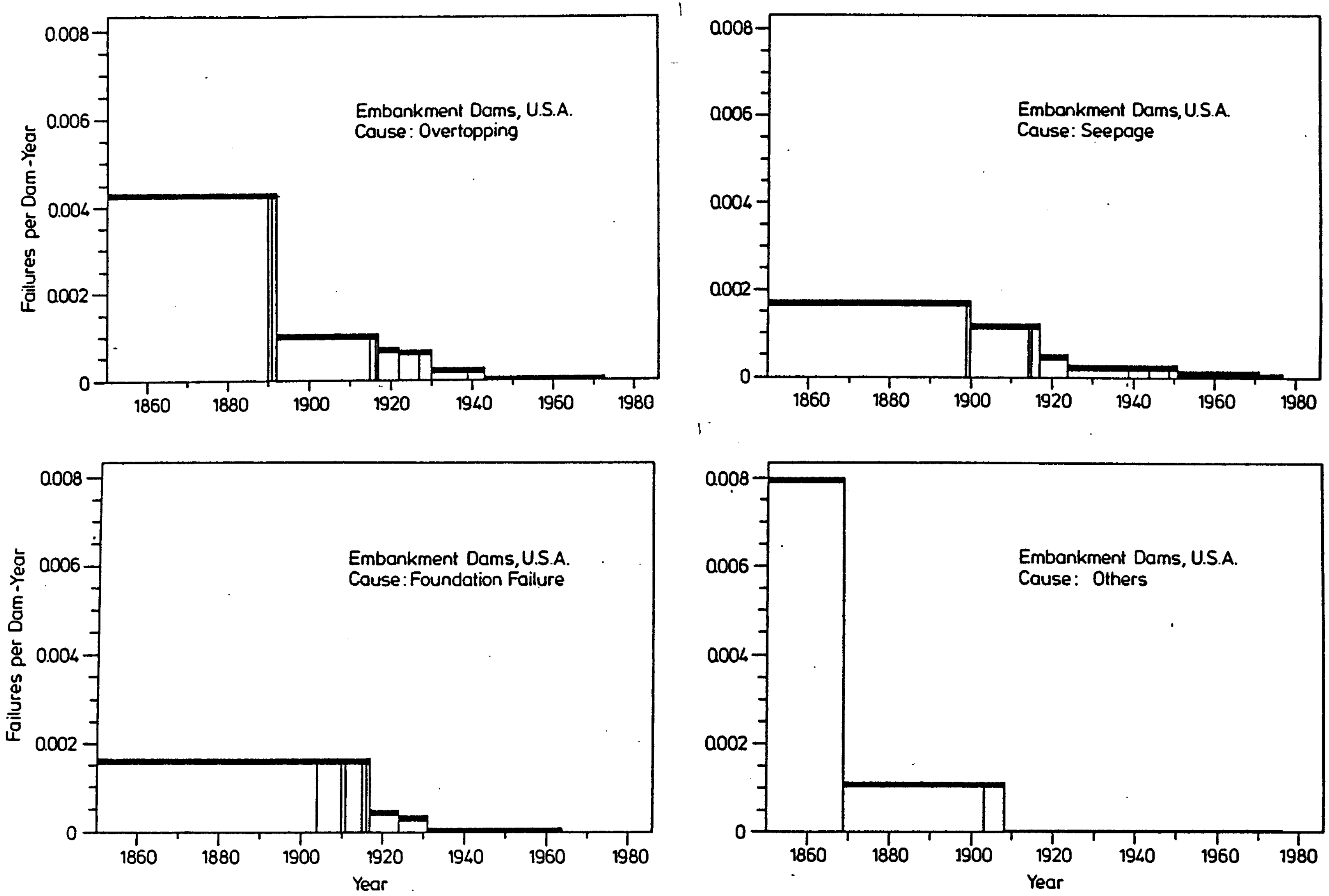

Fig. 2: Isotonic regression estimates for the failure rate per operation year, $\hat{L}$, by causes of failures.

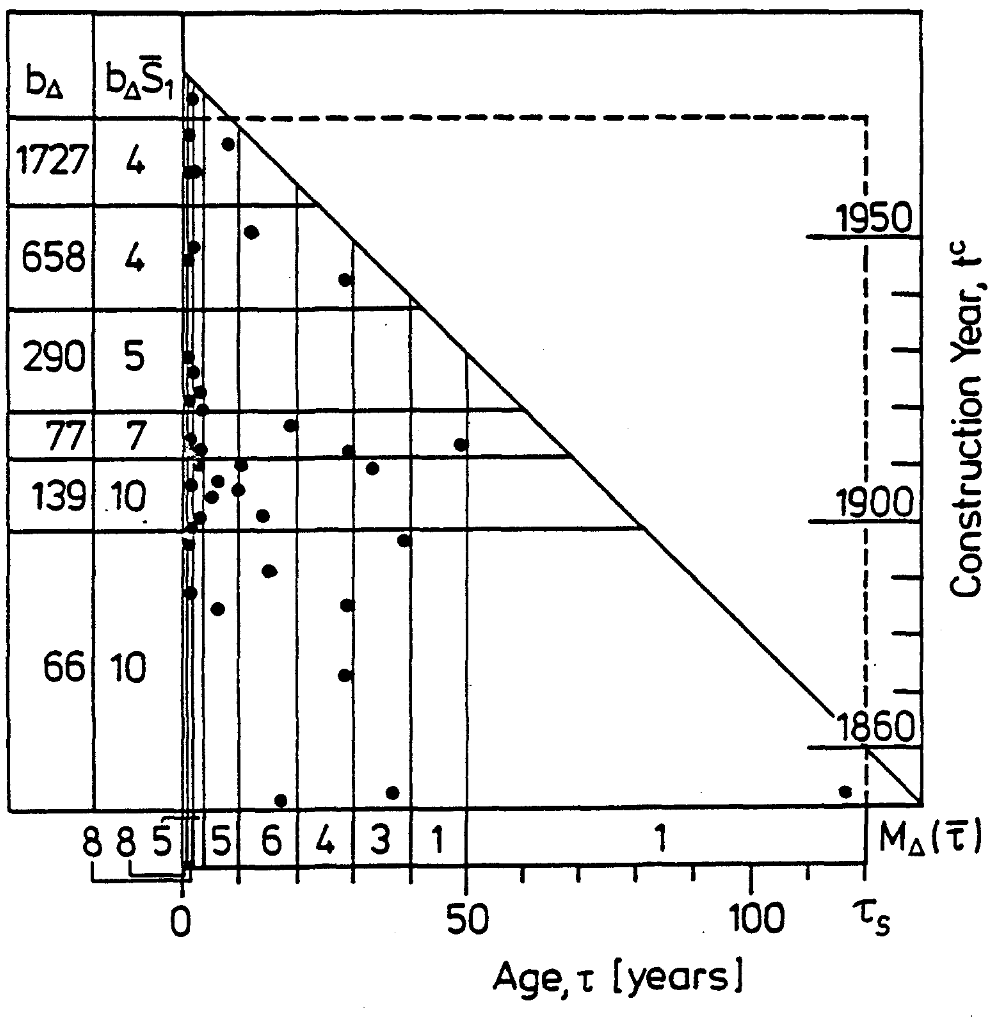

Fig. 3: Actuarial failure date matrix for embankment dams, USA, including the specific interval structure. The corresponding interval values for b_Δ, $b_\Delta\bar{S}_1$, and M_Δ are given along the t^c and τ axes respectively.

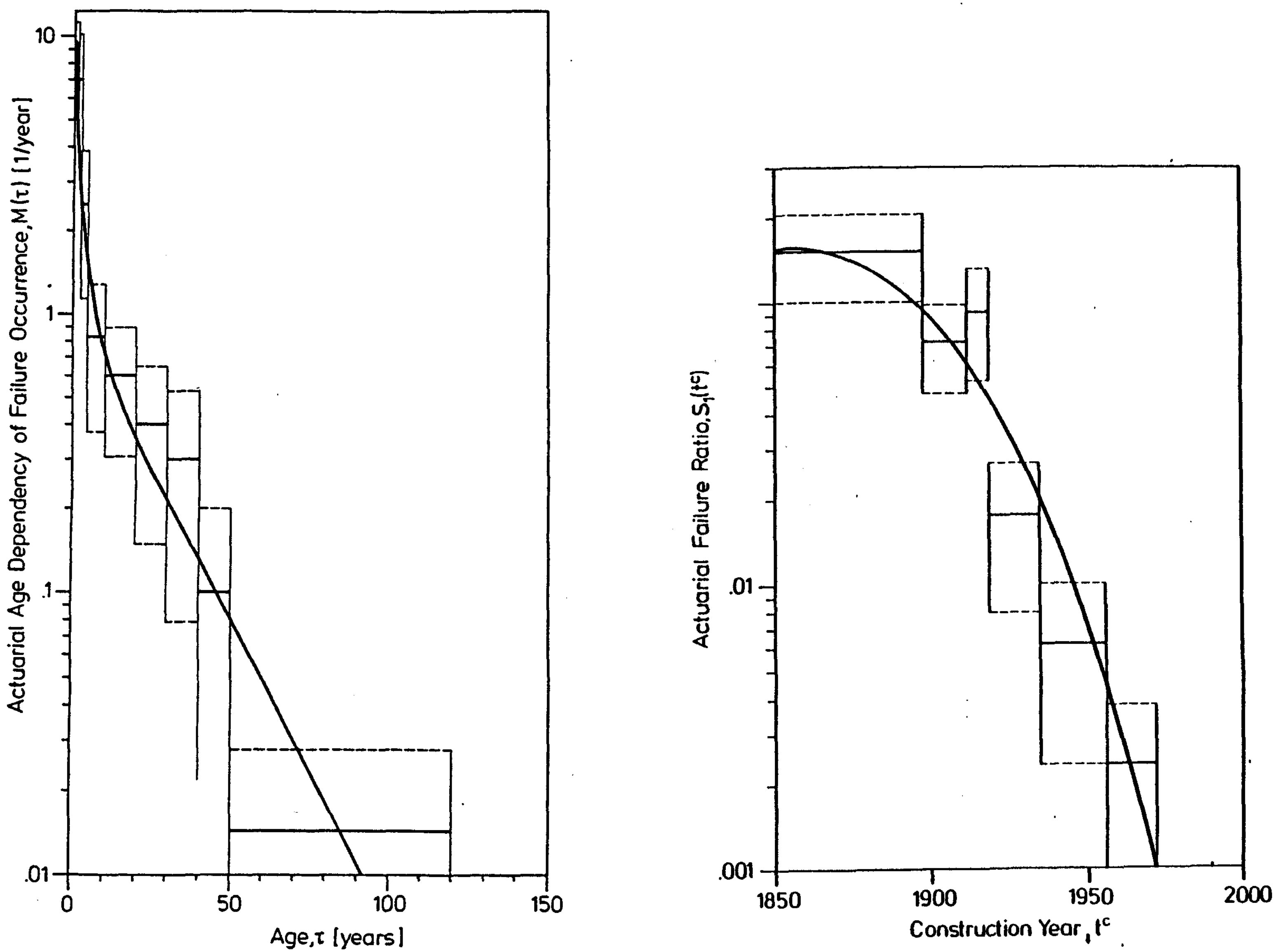

Fig. 4: Actuarial age dependency of failure occurrence, $M(\tau)$, and actuarial failure ratio, $S_1(t^C)$, plotted as bars in the τ and t^C intervals of Fig. 3 respectively together with 68.3 % confidence intervals.

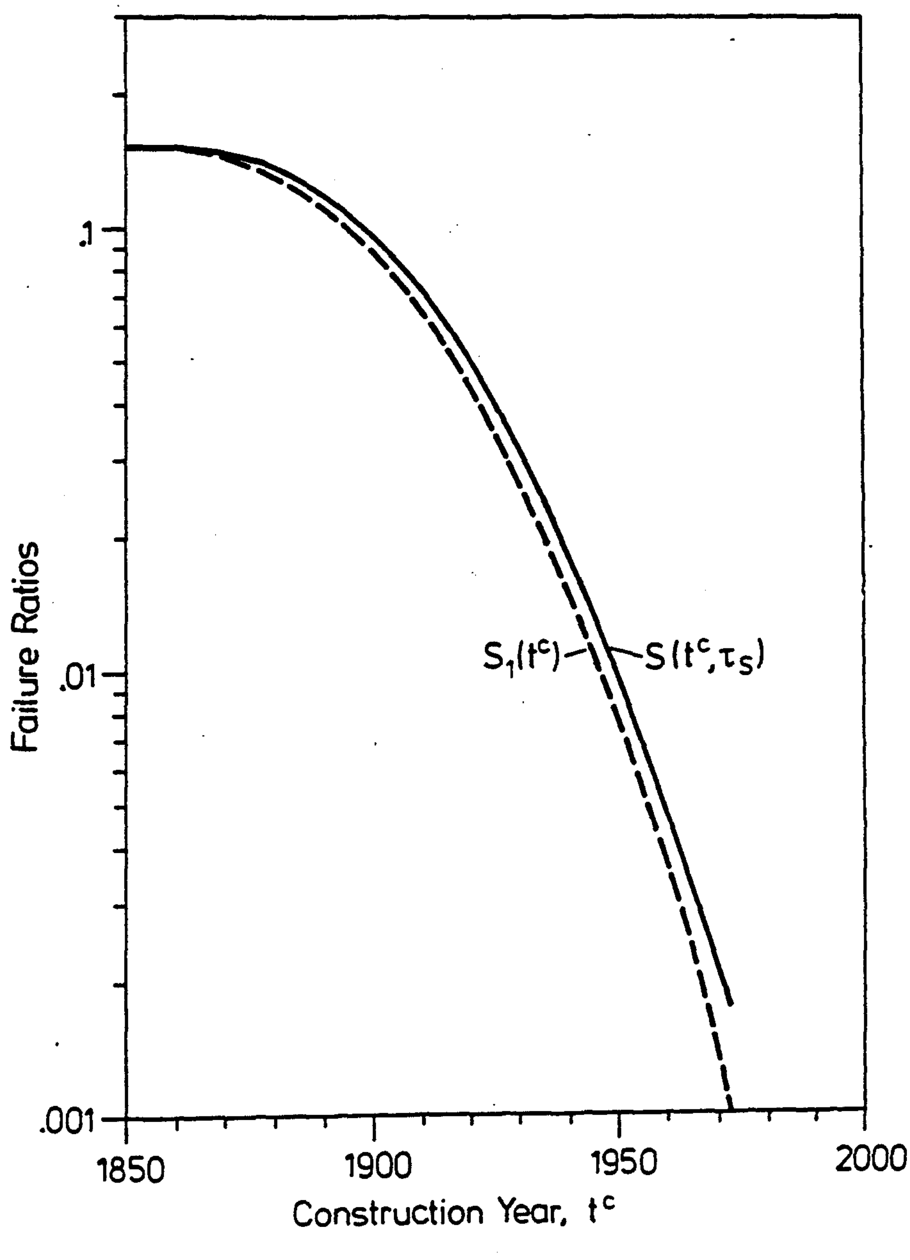

Fig. 5: Comparison of the actuarial function S_1 from Fig. 4 with the completed function S.

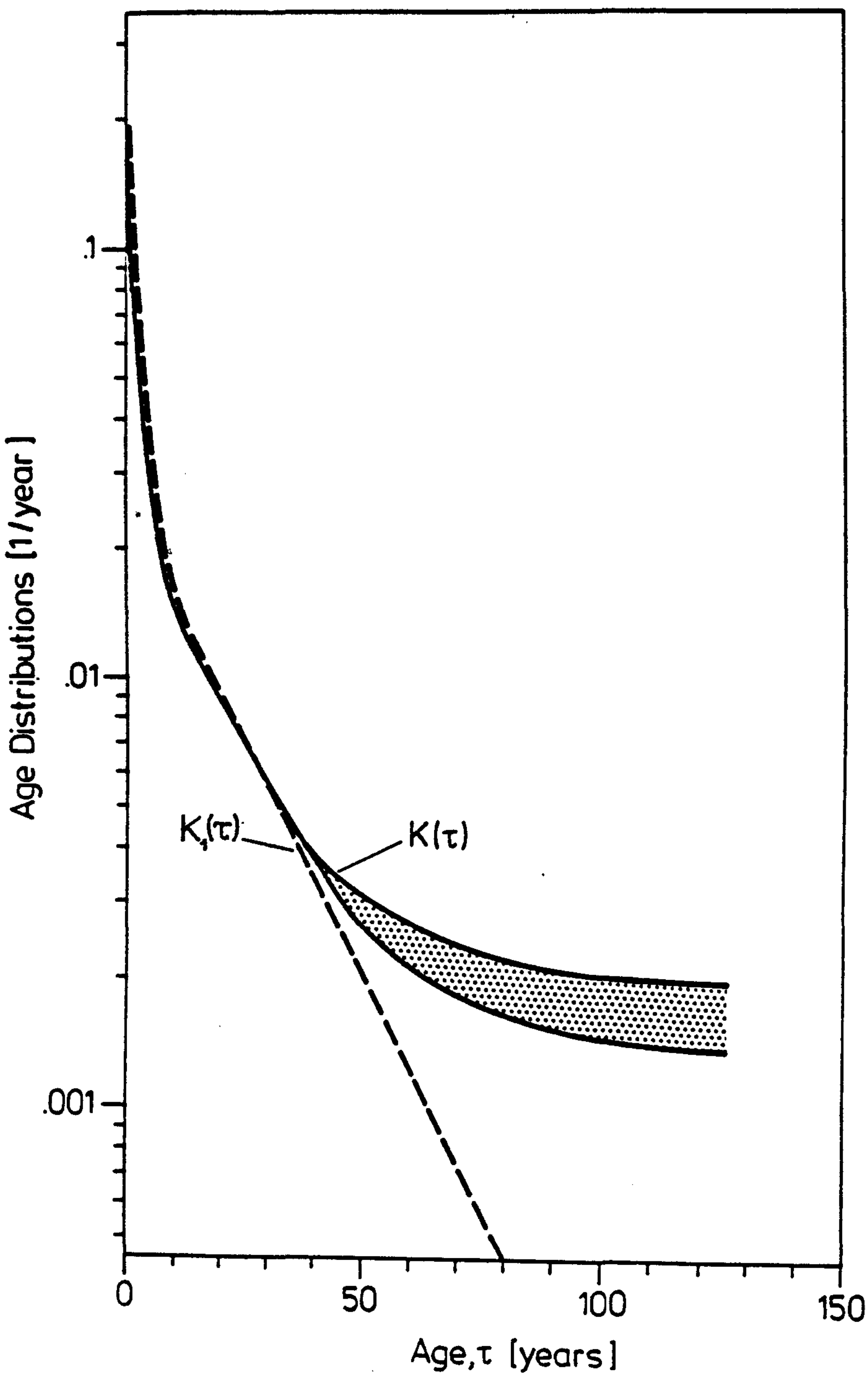

Fig. 6: Comparison of the actuarial function K_1 (K_1 is the normalized M) from Fig. 4 with the completed function K.

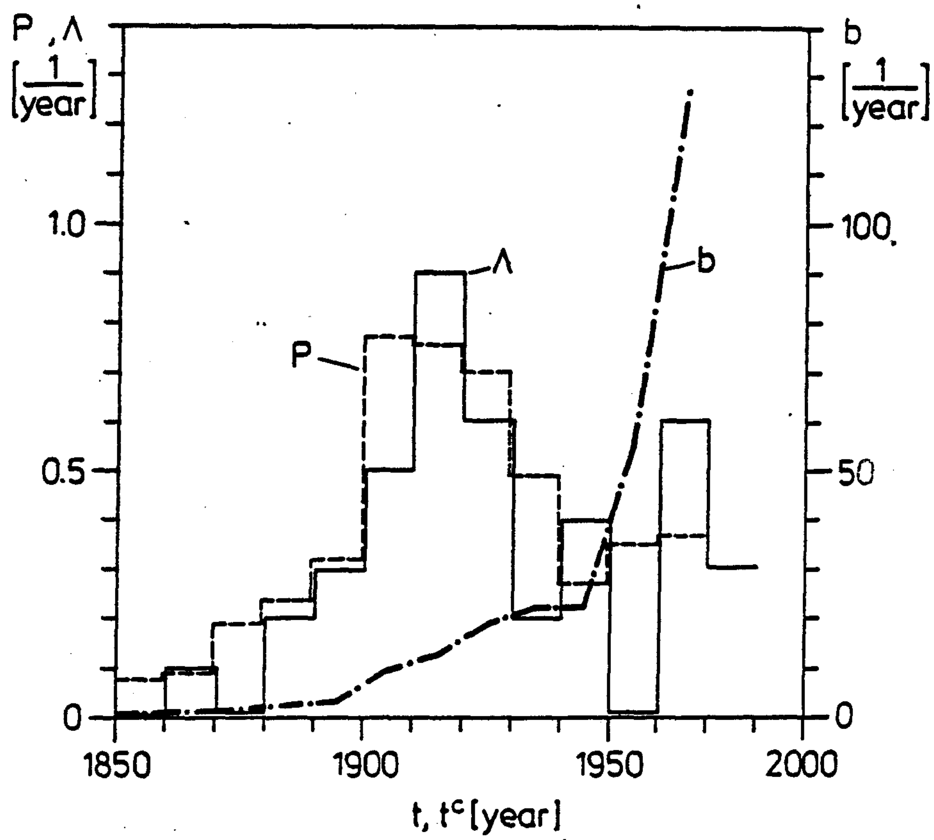

Fig. 7: Comparison of failure potential, $P(t^c)$, and actuarial failure rate, $\Lambda(t)$ (per calendar year). Dashed-dotted line: annual dam construction rate $b(t^c)$ (average values per decade).

Embankment dams, USA

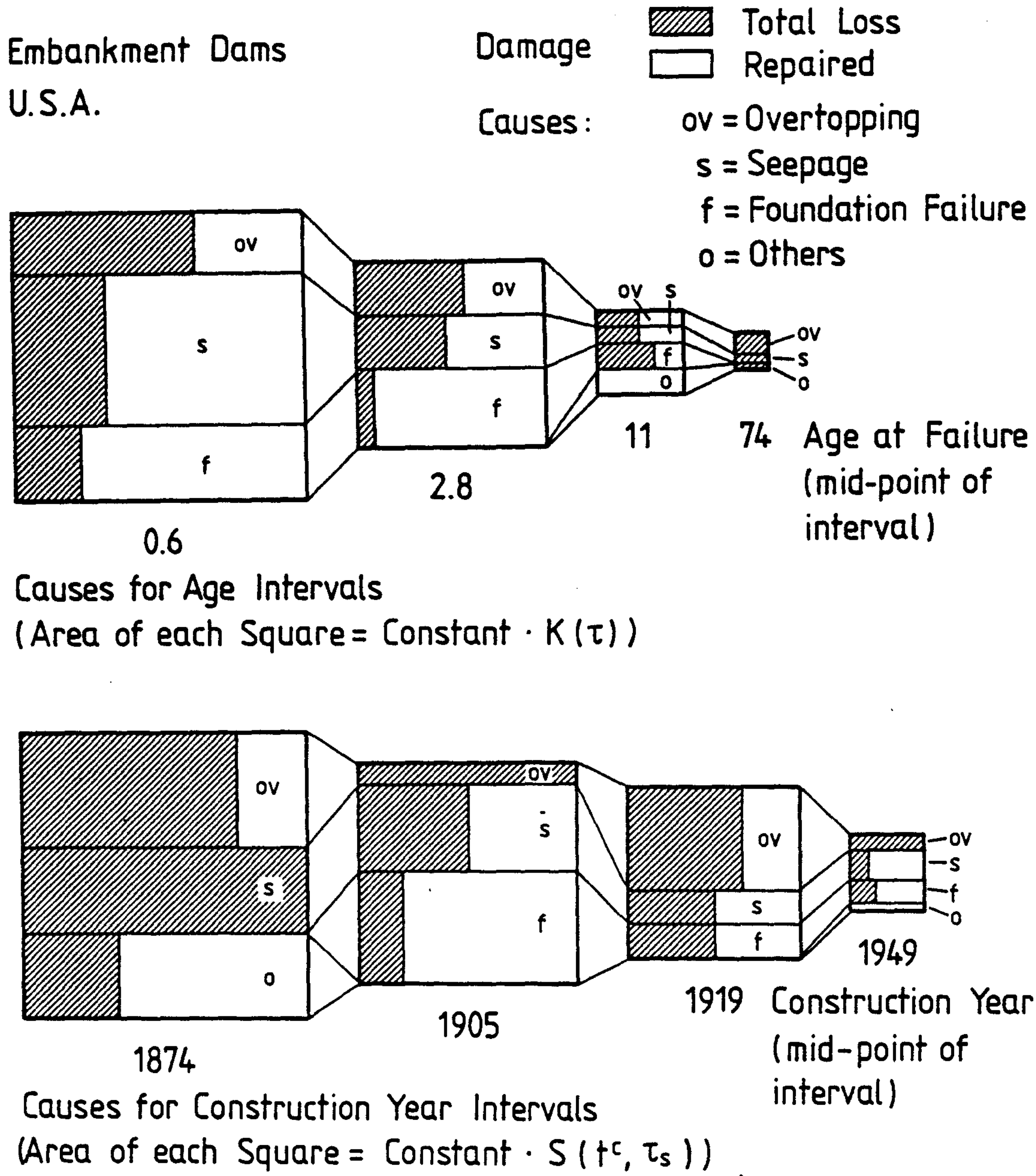

Fig. 8: Causes of failures by age and by construction year. Interval estimates. Same population of dams as in Figs. 3 to 7.

LIST OF REFERENCES

1. ICOLD: World Register of Dams, Edition 1973.

   ICOLD: First Updating as of Dec. 1974 of the World Register of Dams, (1976).

   ICOLD: Second Updating as of Dec. 1977 of the World Register of Dams, July (1979).

2. N.J. Schnitter, "A Short History of Dam Engineering", Water Power, p. 142-148, April (1967).

3. N. Schnitter, "Statistische Sicherheit der Talsperren", Wasser, Energie, Luft, 68, H. 5, S. 126-129,(1976).

4. P. Rißler, "Zur Sicherheitsdiskussion über Talsperrendämme", Wasserwirtschaft, 71, H. 7+8, S. 200-205,(1981).

5. J.L. Serafim, "Safety of Dams Judged from Failures," Water Power & Dam Construction, 33, Dez. (1981).

6. A. Vogel, "Talsperrenbrüche und ihre Ursachen", Dissertation, 147 S., Wien (1982).

7. H. Blind, "Sicherheit von Talsperren", Wasserwirtschaft, 72, H. 3, S. 84-90 (1982).

8. R.E. Barlow, D.J. Bartholomew, J.M. Bremner, H.D. Brunk, "Statistical Inference under Order Restrictions," John Wiley & Sons, New York, (1972).

9. G. Campbell and K.O. Ott, "Statistical Evaluation of Major Human Errors During the Development of New Technological Systems," Nucl. Sci. and Eng., 71, 267 (1979).

10. K.O. Ott and H.J. Hoffmann, "Statistical Trend Analysis Methodology for Rare Failures in Changing Technical Systems," Nuclear Research Center Jülich, Jül-Spez-215, July 1983.

11. H.-J. Hoffmann and K.O. Ott, "Safety Trend Analysis: Construction-Year and Age Dependency in Technical Systems," Nuclear Research Center Jülich, Jül-Spez-219, September 1983

12. International Commission on Large Dams, "Lessons from Dam Incidents," Paris (1974).

13. USCOLD "Lessons from Dam Incidents (USA)," ASCE, (1975).

14. A. Goubet, "Risques associés aux barrages," La Houille Blanche, No. 8, p. 475 - 490 (1979).

15. A. Vogel, "Bibliography of the History of Dam Failures", Wien (1981)

16. A. Vogel, "Data Station for Dam Failures - DSDF - Vienna," Data Memory, Wien (1981).

17. G. Rouvé (Hrsg.), "Vorträge Wasserbau-Seminar, WS 1976/77," in Mitteilungen des Inst. für Wasserbau und Wasserwirtschaft, RWTH Aachen, (1977).

18. H.H. Thomas, "The Engineering of Large Dams. Part I.," John Wiley & Sons, London (1976).

19. C.H. Mallet u. J. Pacquant, "Erdstaudämme", VEB Verlag Technik Berlin (1954).

20. J.L. Serafim, "Lessons from Experience and Research on the Safety of Dams," 2nd International Conference in Structural Safety and Reliability, ICOSSAR, Munich, Germany (1977).

21. A.K. Biswas u. S. Chaterjee, "Dam Disasters: An Assessment," Engineering Journal, March (1971).

22. A.O. Babb, "Catalog of Dam Disasters, Failures and Accidents," US Department of the Interior, Bureau of Reclamation, Washington D.C., (1968).

23. W.R. Hill, "A Classified Review of Dam and Reservoir Failures in the United States," Engineering News, 47, No. 25, (1902).

24. R.B. Jansen, "Dams and Public Safety," US Department of the Interior, Water Power Resources Service, (1980).

25. O. Lanser, "Überblick über Talsperrenkatastrophen der Vergangenheit," Österreichische Wasserwirtschaft, 12, No. 8/9, (1960).

26. O. Schatz u. H. Boesten, "Gebrochene Staudämme," Der Bauingenieur, 17, No. 25/26, (1936).

27. J.L. Sherard et al., "Earth and Earth-Rock Dams," John Wiley and Sons, New York (1963).

28. E.J. Plate, "Bemessungshochwasser und hydrologisches Versorgungsrisiko für Talsperren und Hochwasserrückhaltebecken," Wasserwirtschaft, 72, H. 3, S. 91 - 97 (1982).